Modelling the excavation damaged zone in Callovo-Oxfordian claystone using shear strain localisation

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Excavation damaged zone

Long-term management of radioactive wastes

Intermediate
(long-lived)
&
high activity
wastes

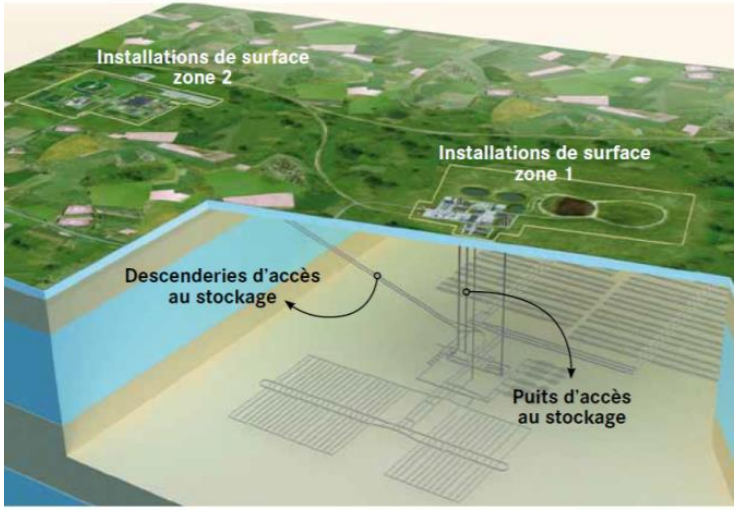
Deep geological disposal

Repository in deep geological media with good confining properties

(Low permeability $K<10^{-12}$ m/s)

Underground structures

= network of galleries



Disposal facility of Cigéo project in France
(Labalette et al., 2013)

Excavation damaged zone

Repository phases

Time

Construction

→ Excavation

Maintenance

→ Ventilation

Repository

→ Sealing

Long term

→ Corrosion,
heat generation

Type C wastes (Andra, 2005)

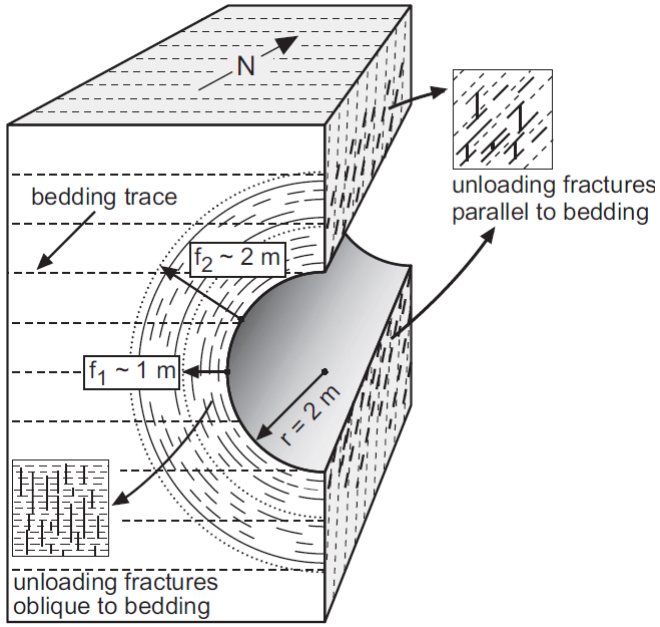
Excavation damaged zone

Excavation Damaged Zone (EDZ)

Construction

Mechanical fracturing

- Excavation
- ↓
- Stress redistribution
- ↓
- Damage / Fracturing
- ↓
- **Coupled processes**
  HM property modifications
- ↓
- Safety function alteration



Fracturing & permeability increase
(several orders of magnitude)

Opalinus clay in Switzerland
(Bossart et al., 2002)

Maintenance

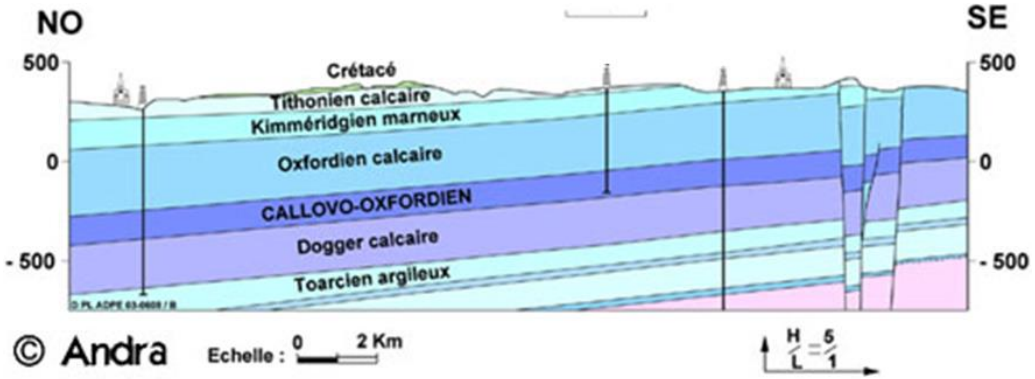
Water transfer

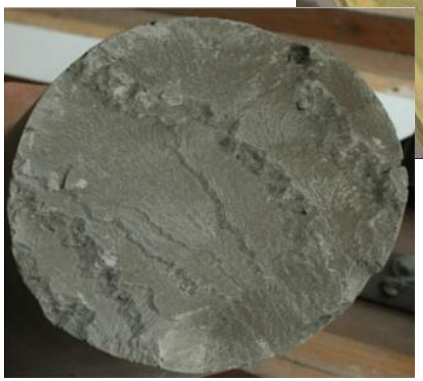
- Galleries ventilation
- ↓
- Air-rock interaction
- ↓
- Drainage / desaturation
- ↓
- Modification of the
  water transfer

Excavation damaged zone

Callovo-Oxfordian claystone (COx)

Sedimentary clay rock (France).





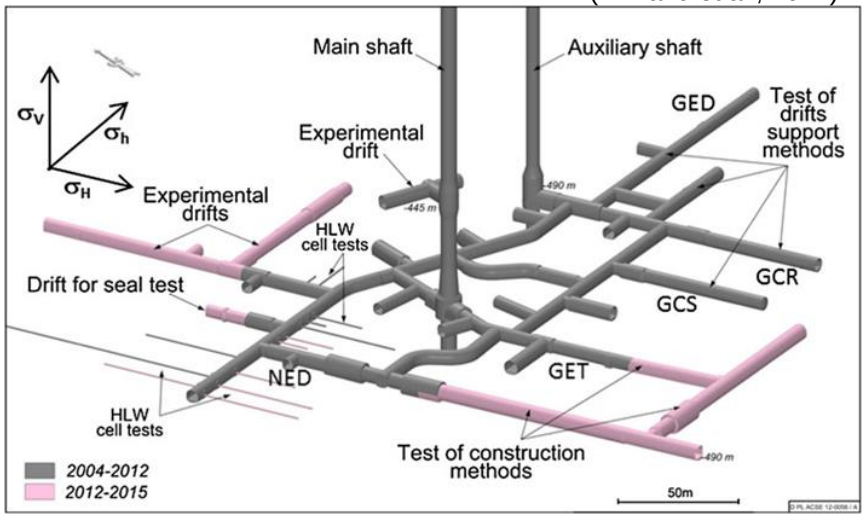
Borehole core samples
(Andra, 2005)

- Underground research laboratory

Feasibility of a safe repository

France (Meuse / Haute-Marne, Bure)

(Armand et al., 2014)

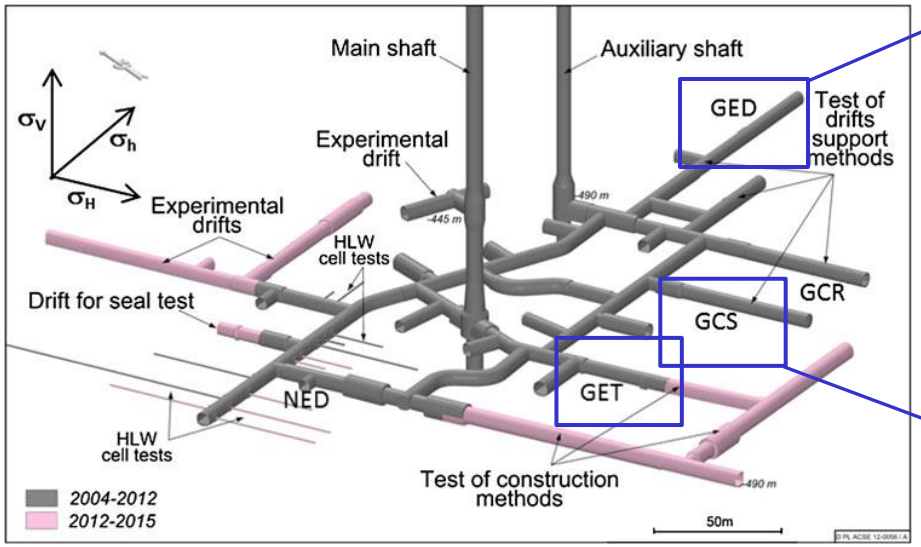


Excavation damaged zone

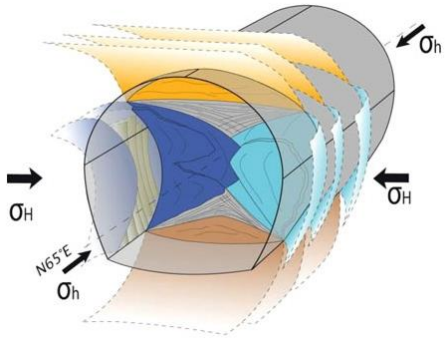
***In situ* evidences (Andra) :** (Armand et al. 2014)

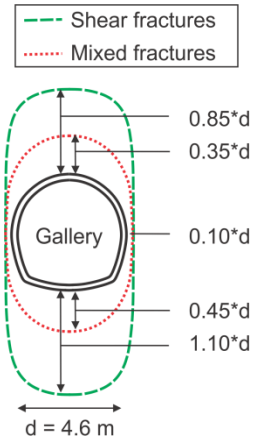
Anisotropy: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

- material : cross-anisotropy

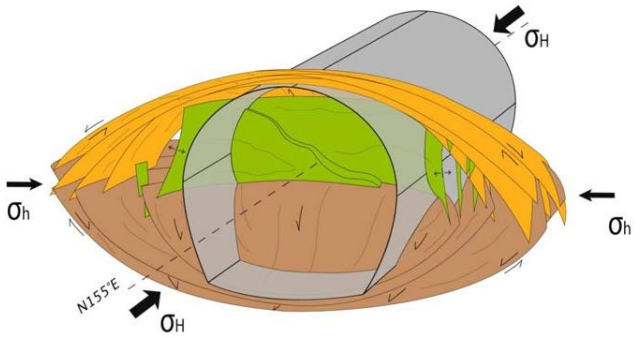


Galery // to σ_h





Galery // to σ_H



Major issues : prediction of the extension, fracturing structure and properties modifications.

Study : - fractures modelling with shear strain localisation

- influence of permeability variation

Outline

1. CONSTITUTIVE MODELS

2. FRACTURES MODELLING

   - GALLERY // TO σ_h

   - GALLERY // TO σ_H

3. PERMEABILITY EVOLUTION

1.1 Strain localisation with regularization - Coupled 2d gradient model : (Chambon *et al.*, 1998 and 2001)

The continuum is enriched with microstructure effects. The kinematics include the classical one (macro) and the microkinematics (Toupin 1962, Mindlin 1964, Germain 1973).

Biphasic porous media : solid + fluid (Collin et al., 2006)

Balance equations for biphasic porous media :

$$\int_\Omega \left(\sigma_{ij} \frac{\partial u_i^*}{\partial x_j} + \Sigma_{ijk} \frac{\partial^2 u_i^*}{\partial x_j \partial x_k} \right) d\Omega = \int_\Omega G_i u_i^* d\Omega + \int_{\Gamma_\sigma} \left(\bar{t}_i u_i^* + \bar{T}_i D u_i^* \right) d\Gamma$$

$$\int_\Omega \left(\frac{\partial M}{\partial t} p_w^* - m_{w,i} \frac{\partial p_w^*}{\partial x_i} \right) d\Omega = \int_\Omega Q\, p_w^*\, d\Omega + \int_{\Gamma_q} \bar{q}\, p_w^*\, d\Gamma$$

Bishop's effective stress : $\sigma_{ij} = \sigma'_{ij} - b_{ij} S_{rw} p_w \delta_{ij}$

Double stress : $\tilde{\Sigma}_{ijk} = f\left(B, \frac{\partial^2 u_i^*}{\partial x_j \partial x_k} \right)$

1.2 Mechanical model :

Linear elasticity : Cross-anisotropic (5 param.) + Biot's coefficient

$$d\varepsilon_{ij}^{e} = D_{ijkl}^{e} d\sigma_{kl}^{'} \qquad E_{//}, E_{\perp}, \nu_{////}, \nu_{//\perp}, G_{//\perp} \qquad \frac{\nu_{\perp//}}{E_{\perp}} = \frac{\nu_{//\perp}}{E_{//}}$$

$$D_{ijkl}^{e} = \begin{bmatrix} \frac{1}{E_{//}} & -\frac{\nu_{////}}{E_{//}} & -\frac{\nu_{\perp//}}{E_{\perp}} & & & \\ -\frac{\nu_{////}}{E_{//}} & \frac{1}{E_{//}} & -\frac{\nu_{\perp//}}{E_{\perp}} & & & \\ -\frac{\nu_{//\perp}}{E_{//}} & -\frac{\nu_{//\perp}}{E_{//}} & \frac{1}{E_{\perp}} & & & \\ & & & \frac{1+\nu_{////}}{E_{//}} & & \\ & & & & \frac{1}{2G_{//\perp}} & \\ & & & & & \frac{1}{2G_{//\perp}} \end{bmatrix}$$

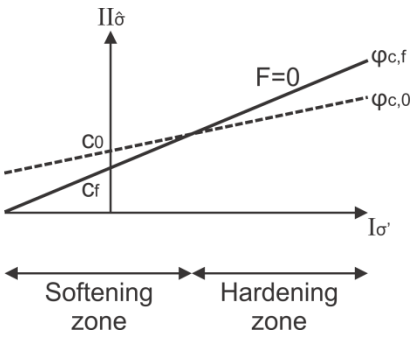
$$b_{ij} = \delta_{ij} - \frac{C_{ijkk}^{e}}{3K_s} \qquad b_{ij} = \begin{bmatrix} b_{//} & & \\ & b_{//} & \\ & & b_{\perp} \end{bmatrix}$$

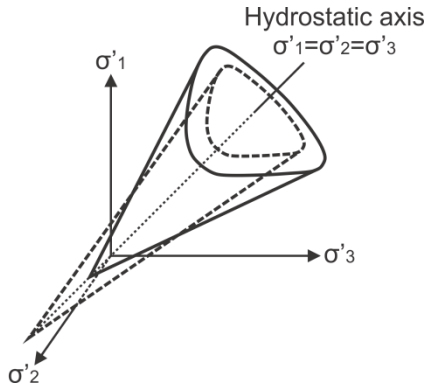
Plasticity :

Van Eeckelen yield surface

Hardening/softening of φ/c :

$$F \equiv II_{\hat{\sigma}} - m\left(I_{\sigma'} + \frac{3c}{\tan\phi_C}\right) = 0$$

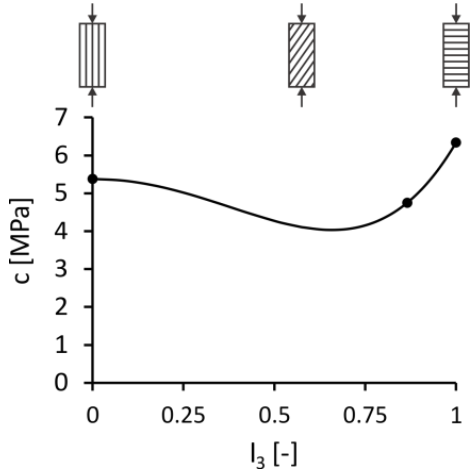




Cohesion anisotropy :

$$c = a_{ij} l_i l_j = \bar{c}\left(1 + A_{11}(1 - 3l_3^2) + b_1 A_{11}^2 (1 - 3l_3^2)^2 + \ldots\right)$$

$$l_i = \sqrt{\frac{\sigma_{i1}^{'2} + \sigma_{i2}^{'2} + \sigma_{i3}^{'2}}{\sigma_{ij}^{'}\sigma_{ij}^{'}}}$$



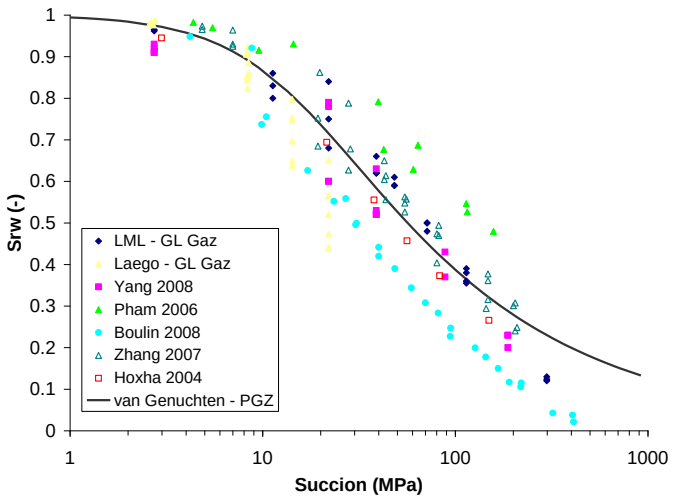
1.3 Flow model :

Advection of liquid phase (Darcy's flow) :

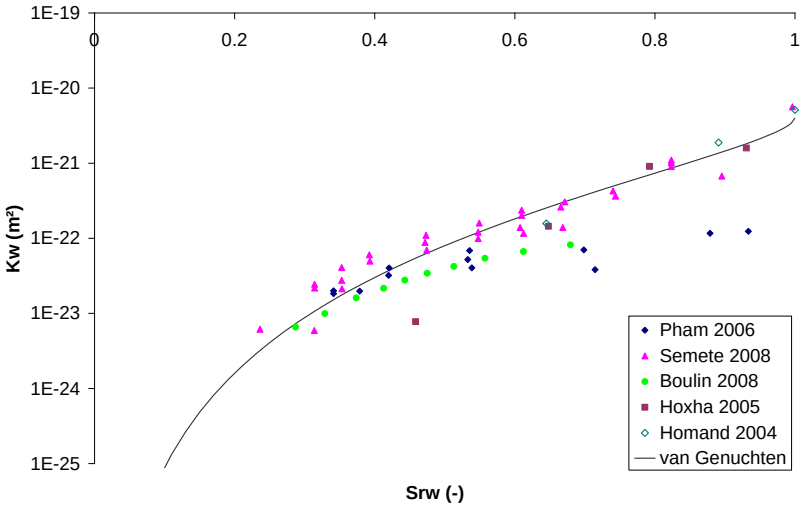
$$m_{w,i} = -\rho_w \frac{k_{ij}\, k_{r,w}}{\mu_w} \frac{\partial p_w}{\partial x_j}$$

Water retention and permeability curves (Van Genuchten's model) :

$$S_{r,w} = S_{res} + (S_{\max} - S_{res}) \left[1 + \left(\frac{p_c}{P_r} \right)^n \right]^{-m}$$



$$k_{r,w} = \sqrt{S_{r,w}} \left[1 - \left(1 - S_{r,w}^{1/m} \right)^m \right]^2$$



2.1 Gallery // to σ_h :

Anisotropic stress state, isotropic model

HM modelling in 2D plane strain state (LAGAMINE-Ulg) :

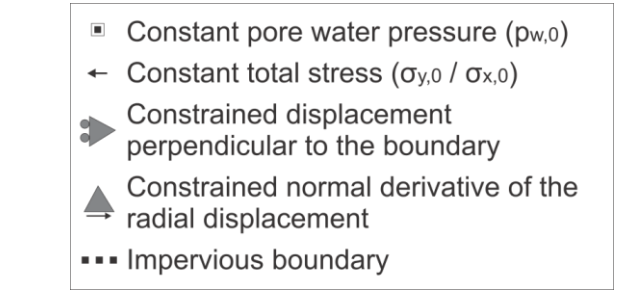
Anisotropy (Andra URL) :

→ hydraulic permeability anisotropy

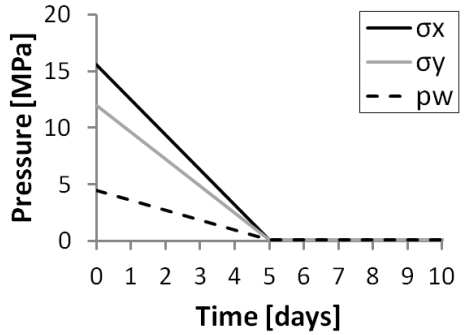
$k_{hor/vert} = 4\ 10^{-20} / 1.33\ 10^{-20}$ [m²]

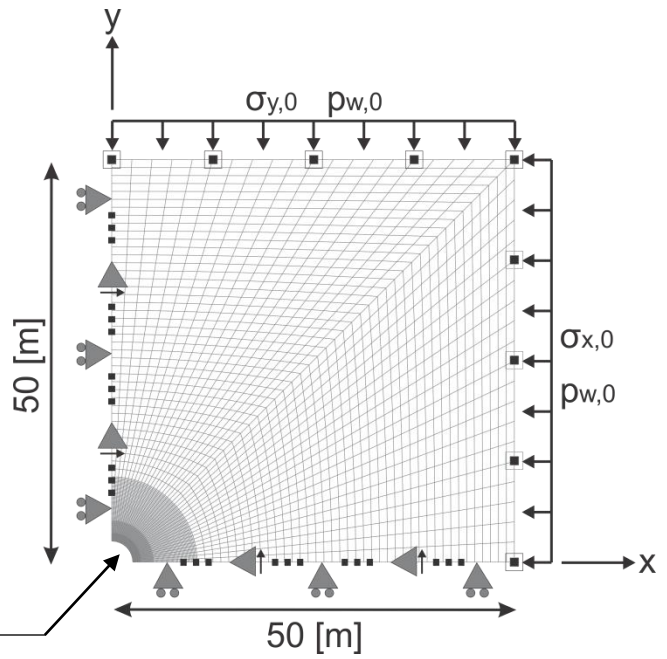
→ initial anisotropic stress state

$p_{w,0} = 4.5$ [MPa]
$\sigma_{v,0} = \sigma_{h,0} = 12$ [MPa]
$\sigma_{H,0} = 1.3\ \sigma_{v,0} = 15.6$ [MPa]



Excavation :





2. Fractures modelling

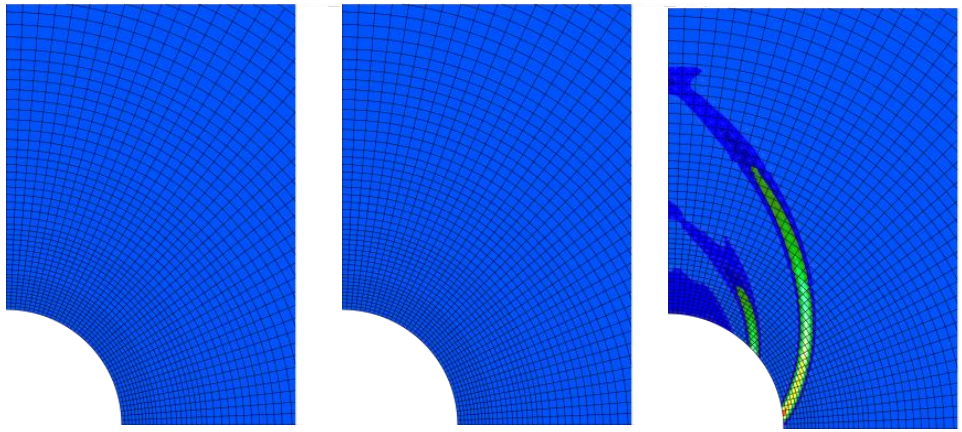
End of excavation ↓

σ/σ_0=0.4 σ/σ_0=0.2 σ/σ_0=0.0

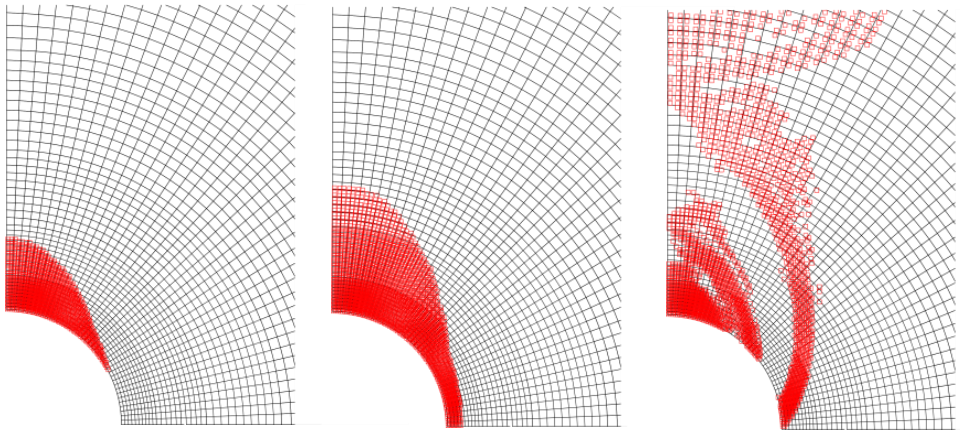
Total deviatoric strain

$$\varepsilon_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$$

0 0.184

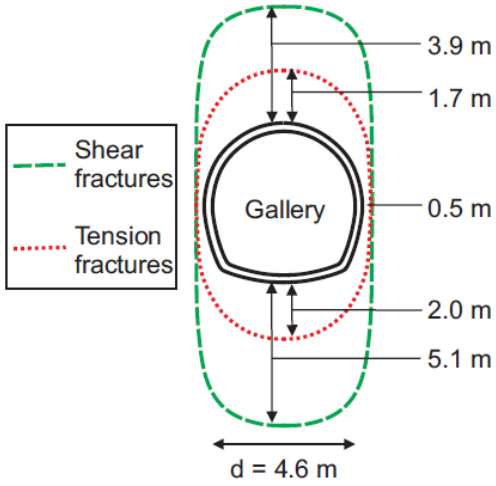


Plasticity

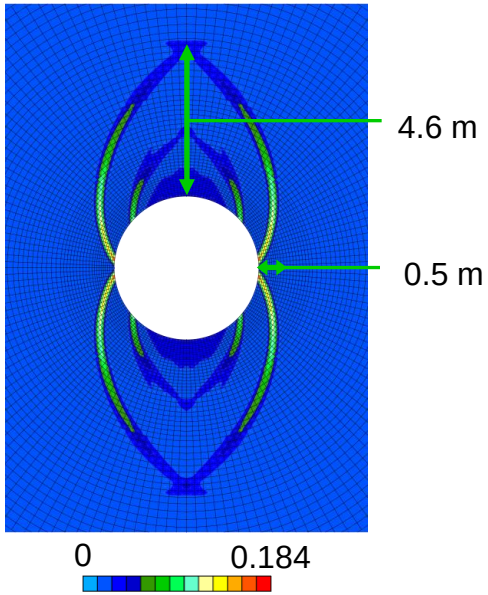


2. Fractures modelling

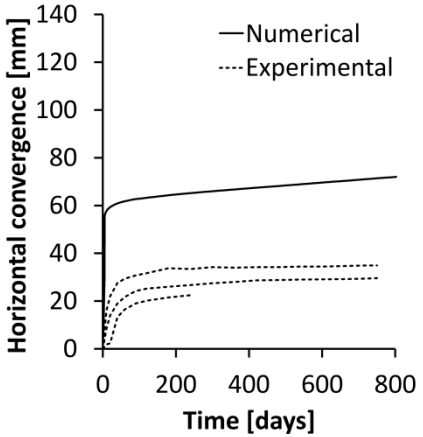
Fractures

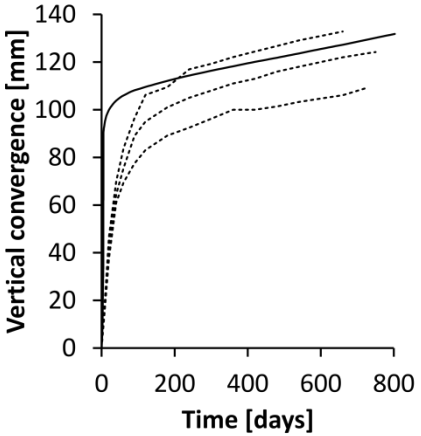


Total deviatoric strain



Convergence



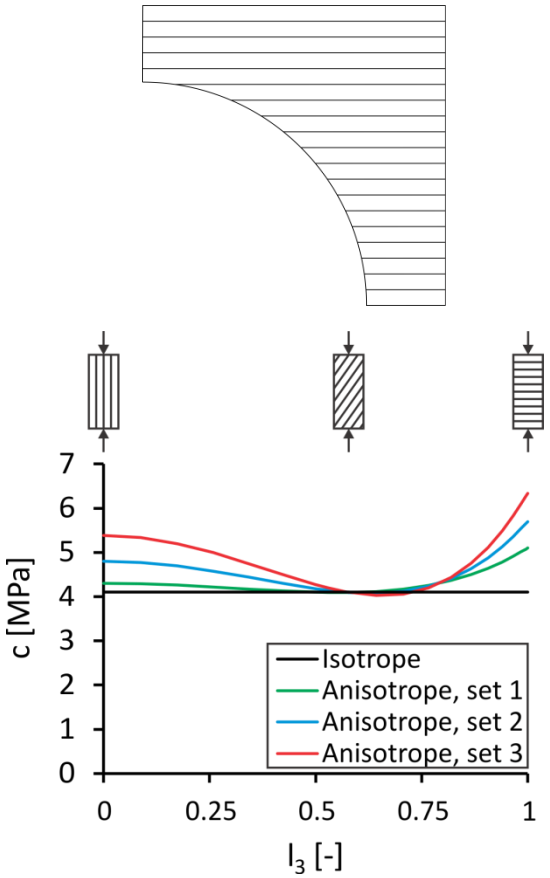


σ anisotropy is the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.

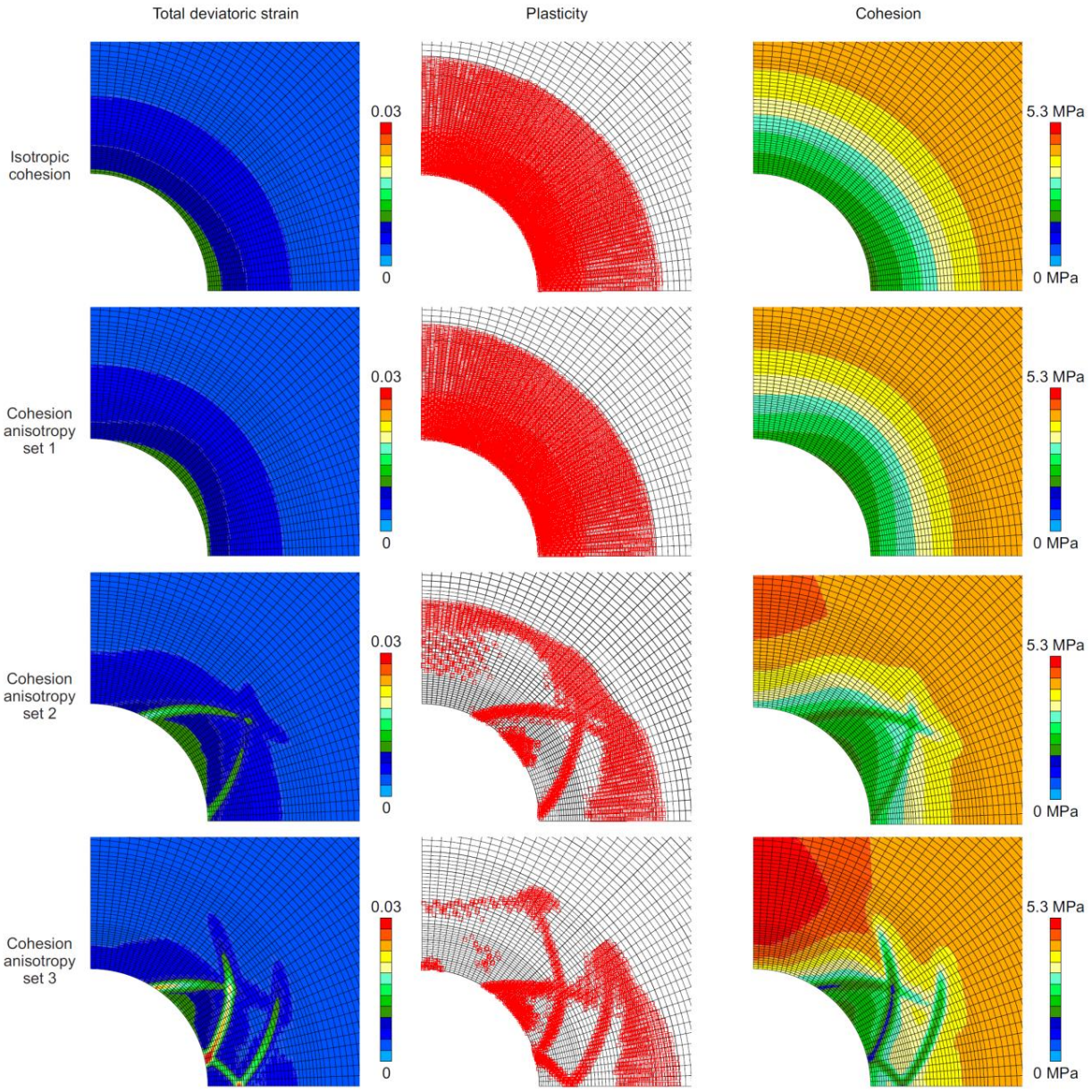
2.2 Gallery // to σ_H :

Isotropic stress state (σ=12 MPa), anisotropic model

HM modelling in 2D plane strain state



End of excavation



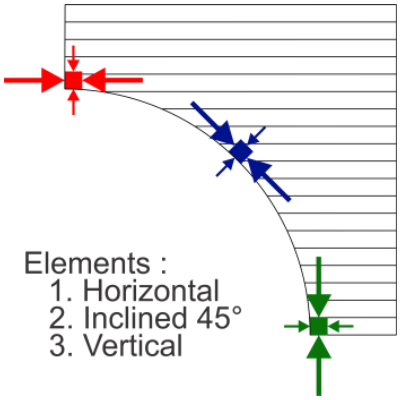
2. Fractures modelling

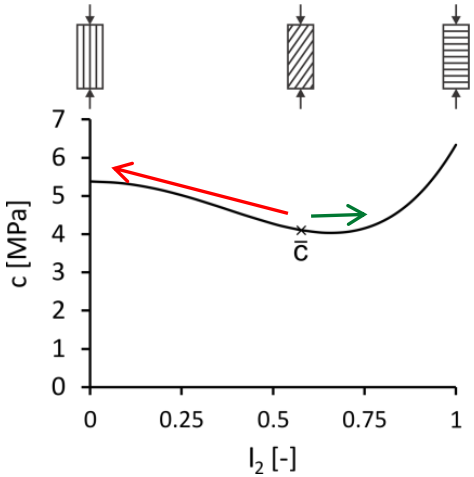
Cohesion evolution :

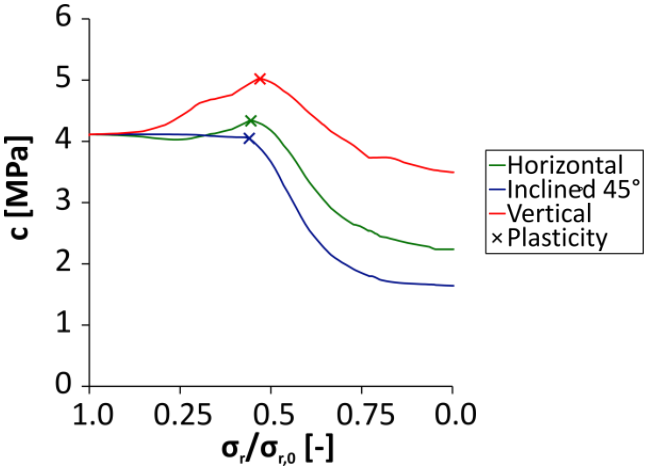
Anisotropy: $c = a_{ij} l_i l_j = \bar{c}\left(1 + A_{11}(1-3l_2^2) + b_1 A_{11}^2 (1-3l_2^2)^2 + \ldots\right)$ $\quad l_i = \sqrt{\dfrac{\sigma_{i1}'^2 + \sigma_{i2}'^2 + \sigma_{i3}'^2}{\sigma_{ij}'\sigma_{ij}'}}$

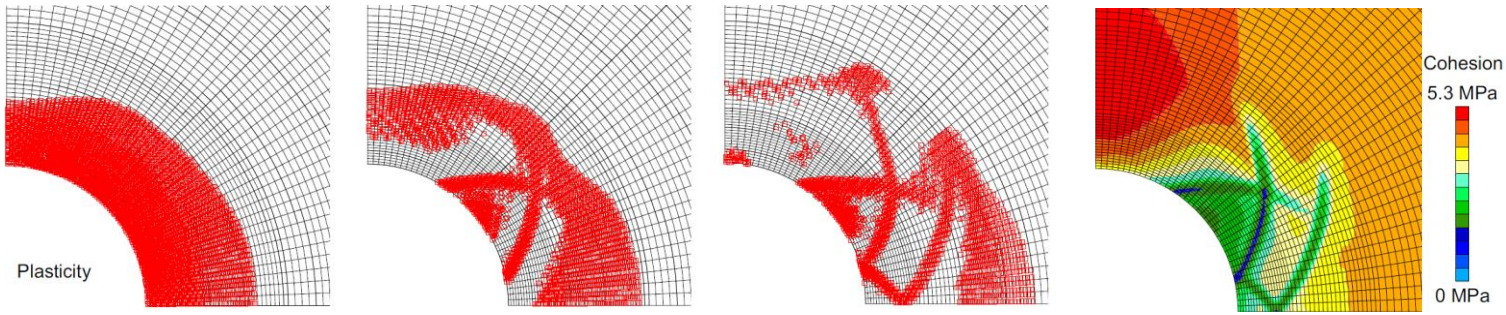
Initially : isotropic σ_{ij} → $c = \bar{c}$ $\quad l_2 = \sqrt{3}/3 = 0.58$

Excavation : $\sigma_r \downarrow$ and $\sigma_{ort} \uparrow$







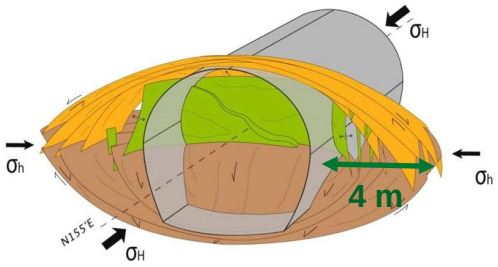


2. Fractures modelling

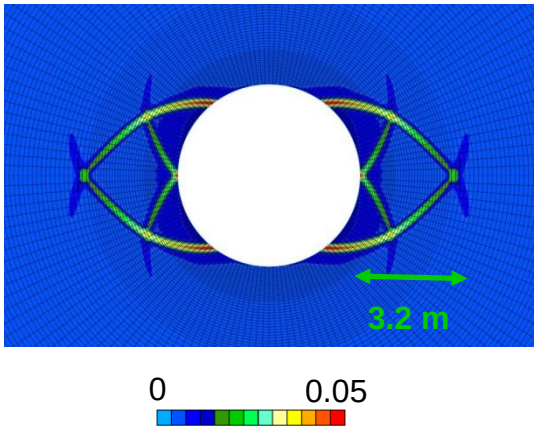
Anisotropic stress state, anisotropic model

$\sigma_{H,0} = 1.3\ \sigma_{v,0} > \sigma_{v,0} = \sigma_{h,0} = 12$ [MPa]

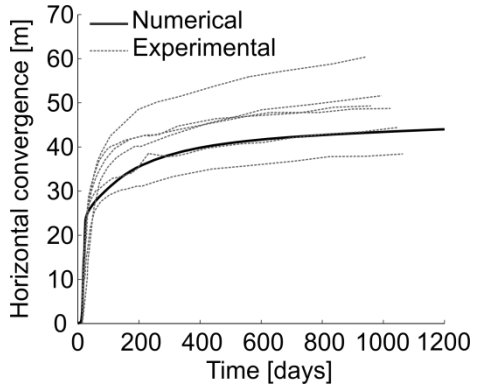
Fractures

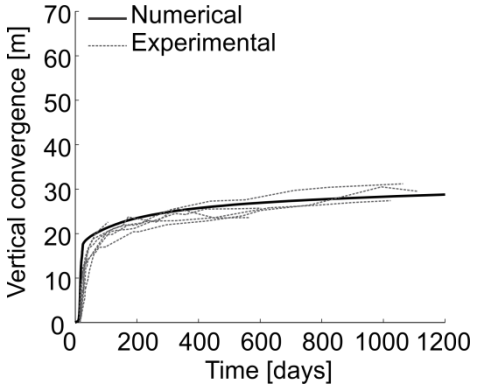


Total deviatoric strain



Convergence





Isotropic stress state in the gallery section does not lead to shear strain localisation unless the material anisotropy is considered.

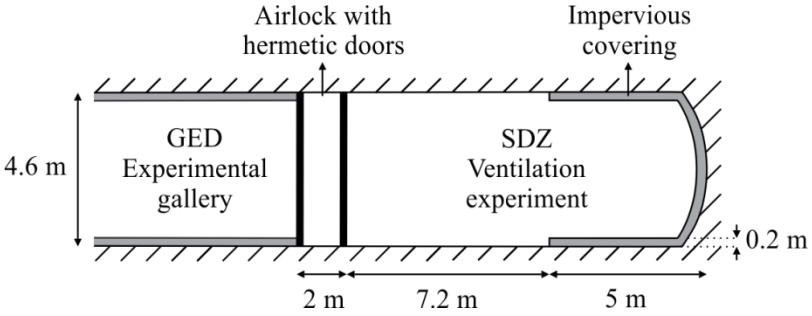
Material anisotropy seems to be the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.

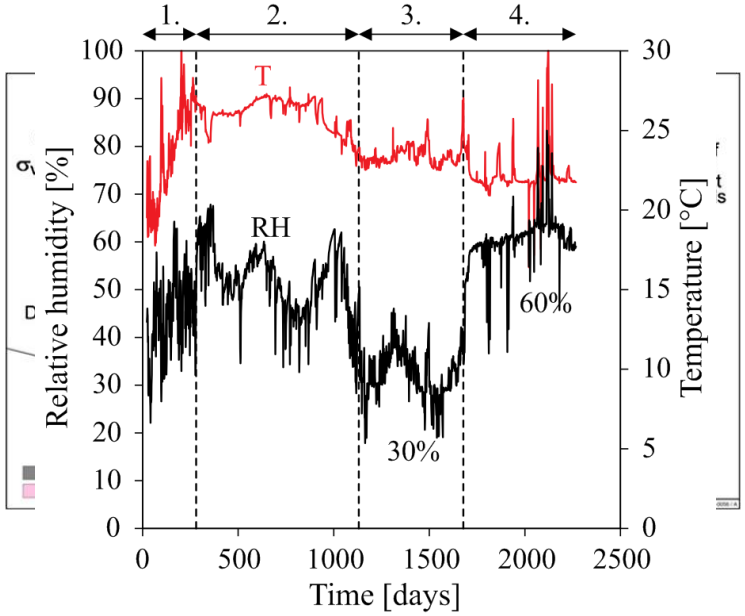
3.1 Large-scale experiment of gallery ventilation (SDZ)

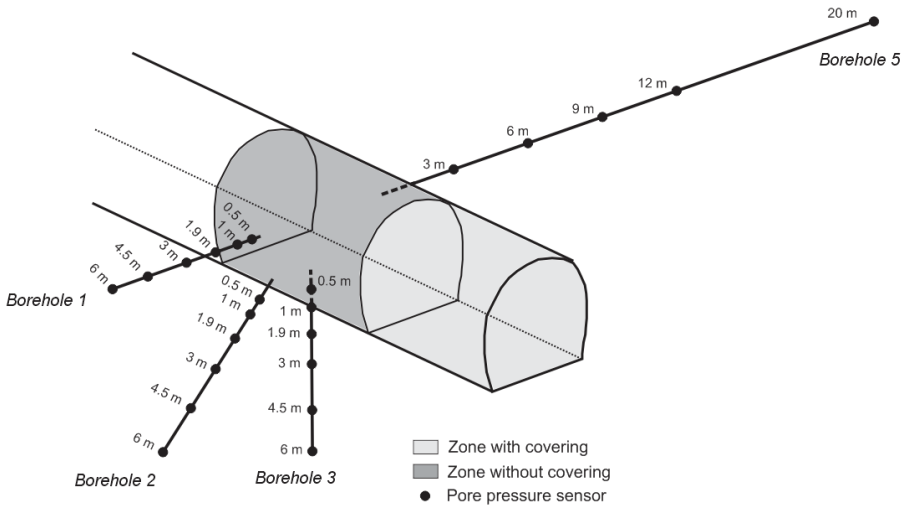
Characterise the effect of gallery ventilation
on the hydraulic transfer around it.

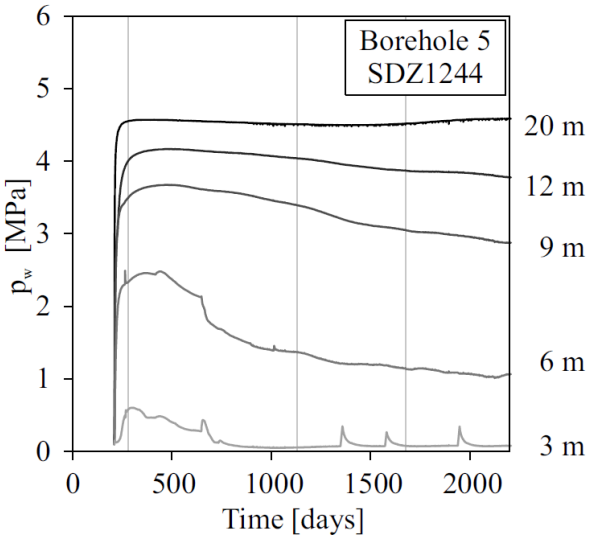
→ drainage / desaturation

→ exchange at gallery wall





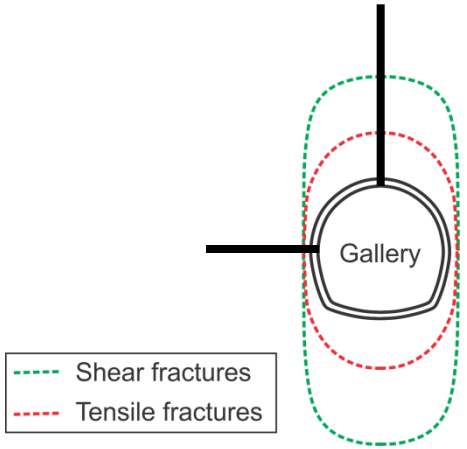


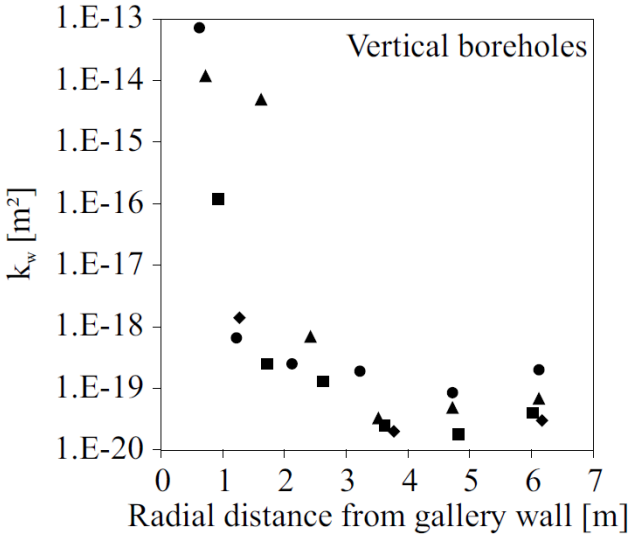


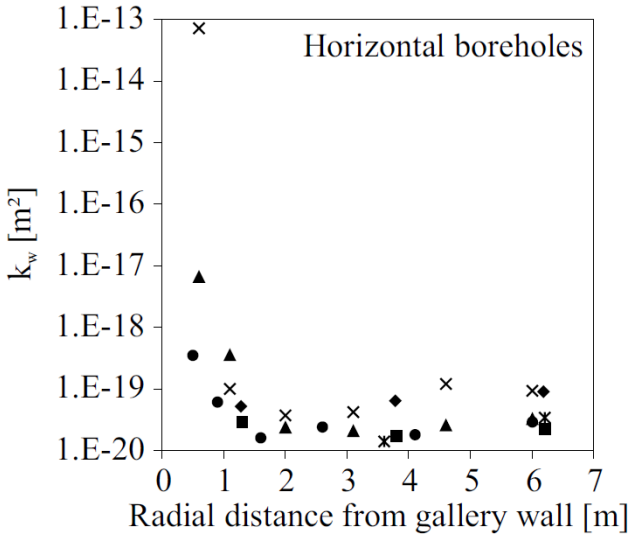
Permeability variation in fractured zone

HM coupling in the EDZ.

Saturated permeability in boreholes







Fracture and rock matrix permeabilities

→ Capture k_w evolution

→ Relation to fractures

3. Permeability evolution

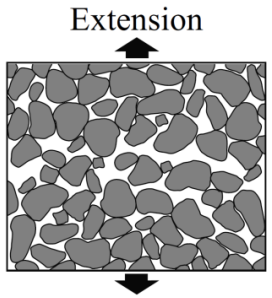
Evolution of intrinsic water permeability

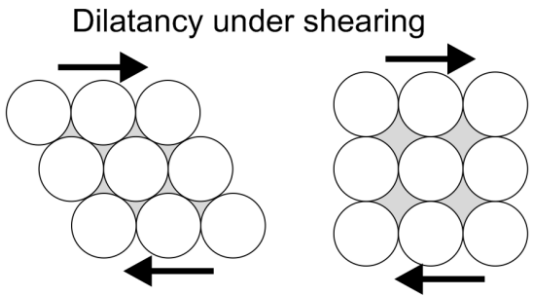
Various approaches: deformation, damage, cracks…

- Relation to deformation

Volumetric effects = increase of porous space
(Kozeny-Carman)

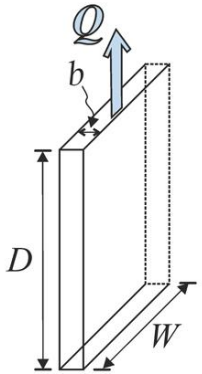
$$k_w = k_{w,0} \frac{(1-\phi_0)^{\xi_1}}{\phi_0^{\xi_2}} \frac{\phi^{\xi_2}}{(1-\phi)^{\xi_1}} \qquad \varepsilon_v = \frac{\varepsilon_{ii}}{3}$$



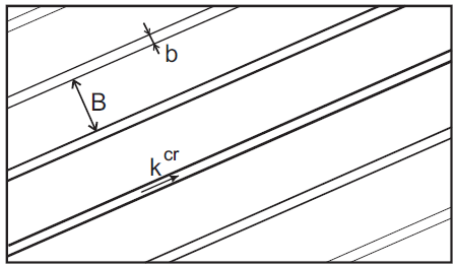


- Fracture permeability

Cubic law for parallel-plate approach
(Witherspoon 1980; Snow 1969, Olivella and Alonso 2008)



$$k_w^{cr} = \frac{b^2}{12}$$



$$k_w = \frac{b^3}{12B}$$

$$b = b_0 + B\left\langle \varepsilon^n - \varepsilon_0^n \right\rangle$$

$$k_w = k_{w,0}\left(1 + A\left\langle \varepsilon^n - \varepsilon_0^n \right\rangle\right)^3$$

Localised deformation
Fracture initiation

- Empirical law

Related to strain localisation effect
Permeability variation threshold

$$k_{w,ij} = k_{w,ij,0}\left(1 + \beta_{per}\left\langle YI - YI^{thr}\right\rangle \hat{\varepsilon}_{eq}^{\ 3}\right) \qquad YI = \frac{II_{\hat{\sigma}}}{II_{\hat{\sigma}}^{p}}$$

Modelling of excavation and SDZ experiment

HM coupling in EDZ

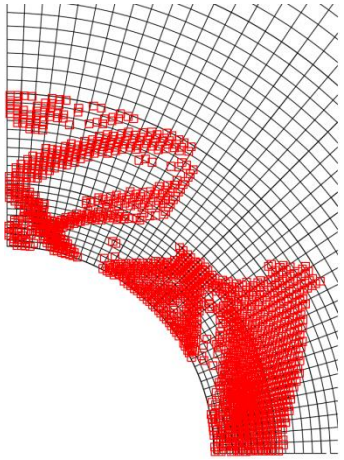
- Gallery excavation

SDZ → GED gallery // σ_h

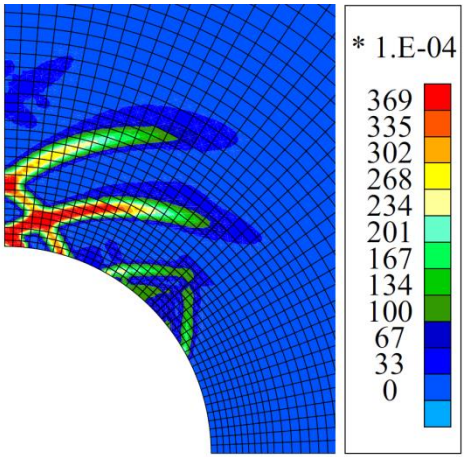
Anisotropic $\sigma_{ij,0}$ and material

→ Localisation zone dominated by stress anisotropy

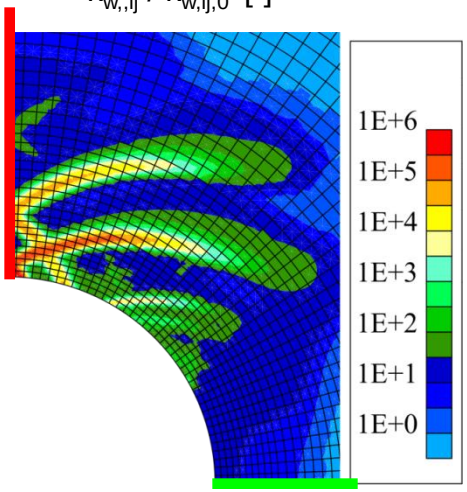
Plasticity



Total deviatoric strain



$k_{w,,ij}$ / $k_{w,ij,0}$ [-]

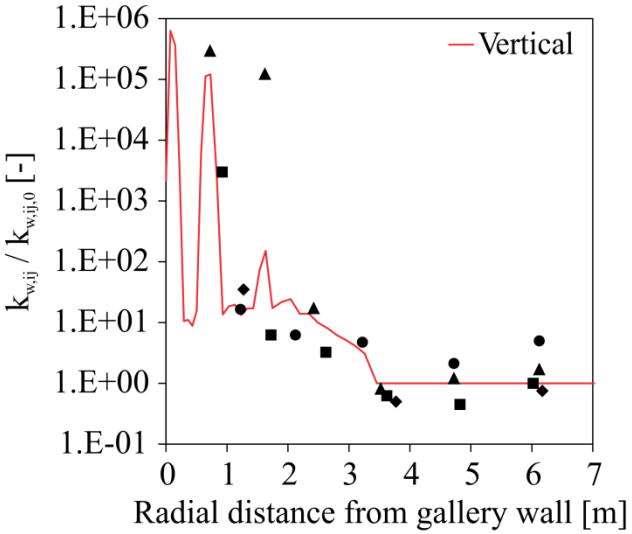


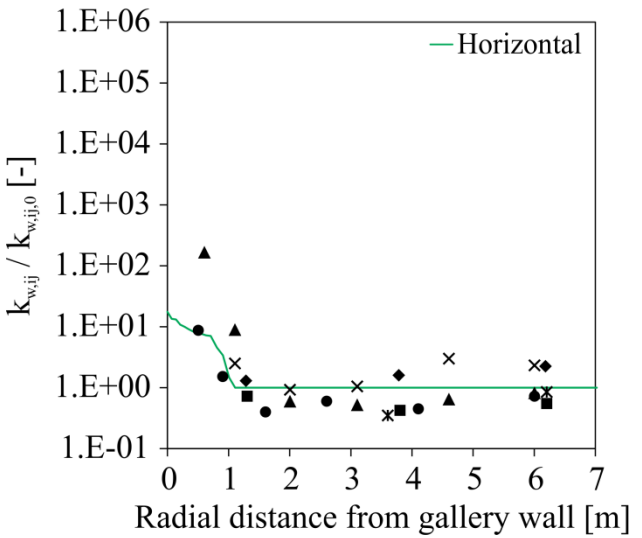
- Intrinsic permeability evolution

$$\frac{k_{w,ij}}{k_{w,ij,0}} = \left(1 + \beta \left\langle YI - YI^{thr} \right\rangle \hat{\varepsilon}_{eq}^{\ 3}\right)$$

$$YI^{thr} = 0.95$$

Cross-sections





Plastic strain and a part of the elastic one → EDZ extension + k_w increase

Modelling of the SDZ experiment

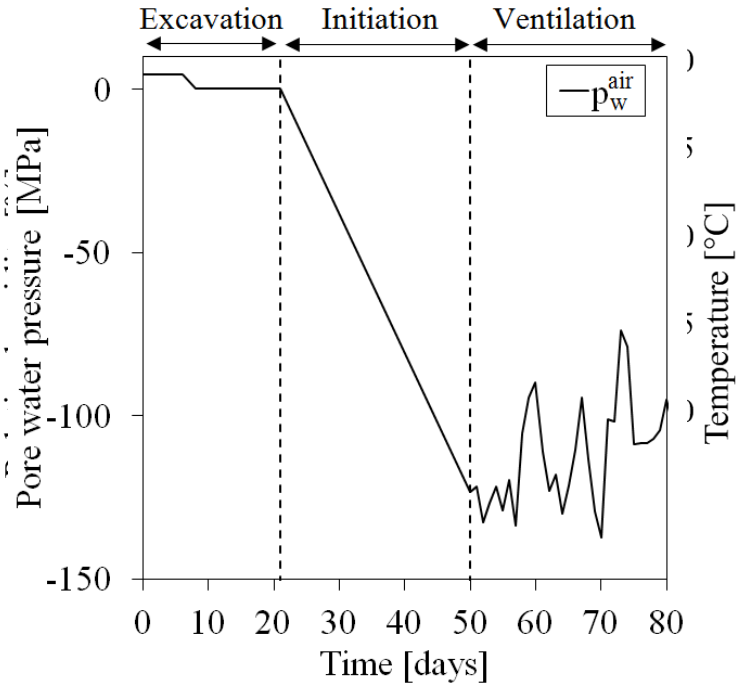
- Water pressure in the cavity air

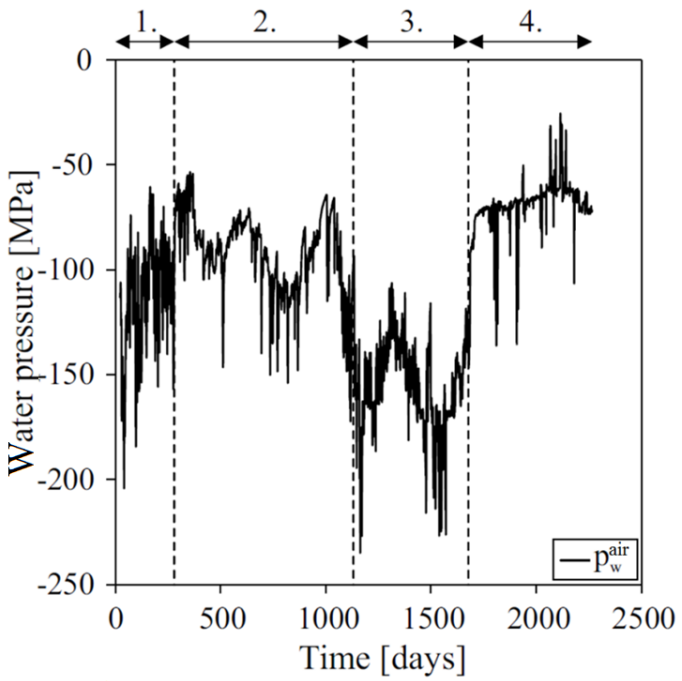
p_w (suction) corresponding to RH and T (Kelvin's law).

$$p_w^{air} = \frac{\rho_w RT}{M_v} \ln(RH) + p_{atm} \qquad \rho_v^{air} = RH \; \rho_v^0$$

Imposed at gallery wall through hydraulic boundary condition.

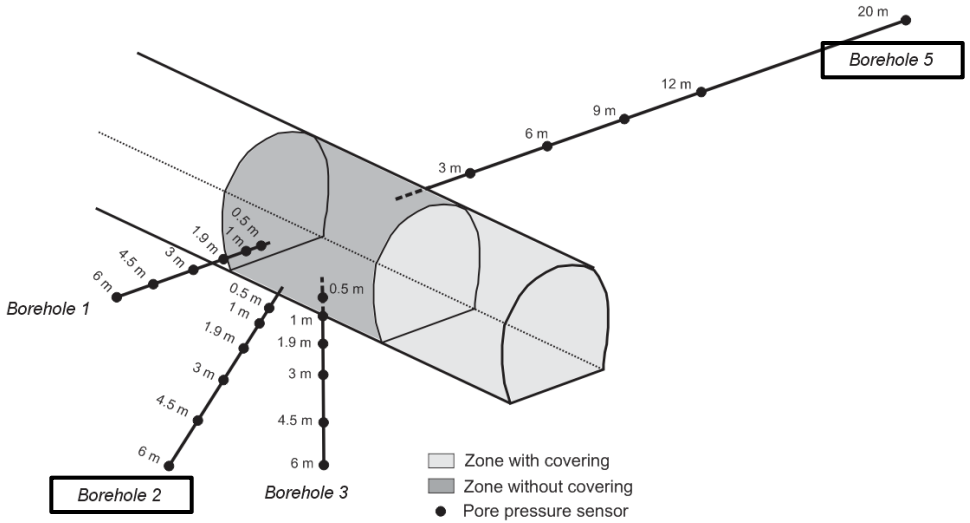
Excavation (RH=100%) → Initiation phase → Ventilation



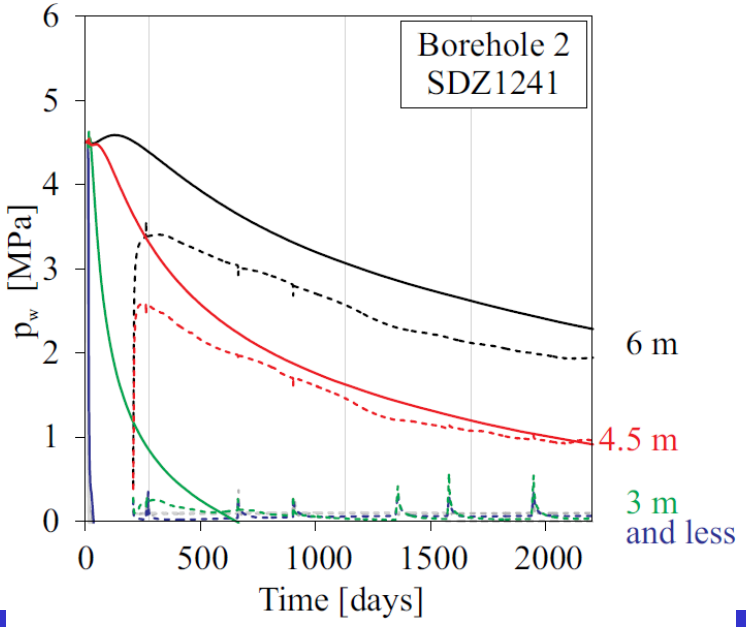


3. Permeability evolution

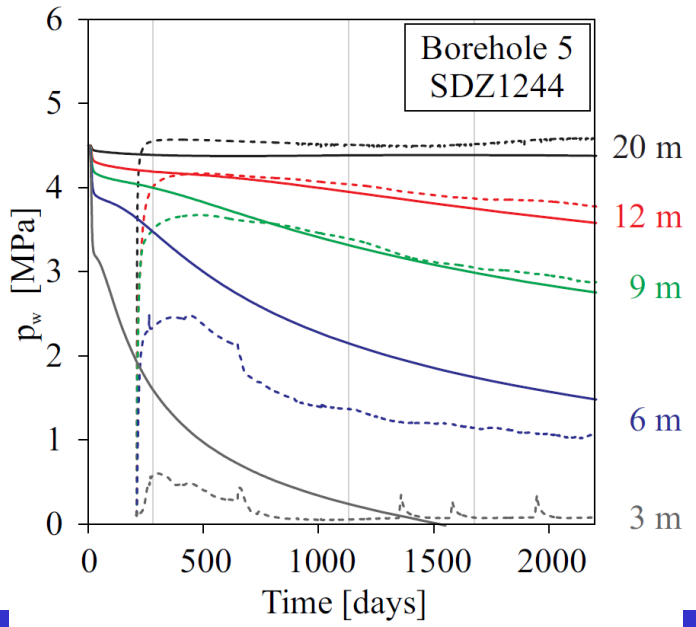
- Drainage / p_w reproduction

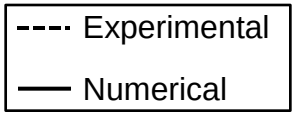


Oblique 45°



Horizontal



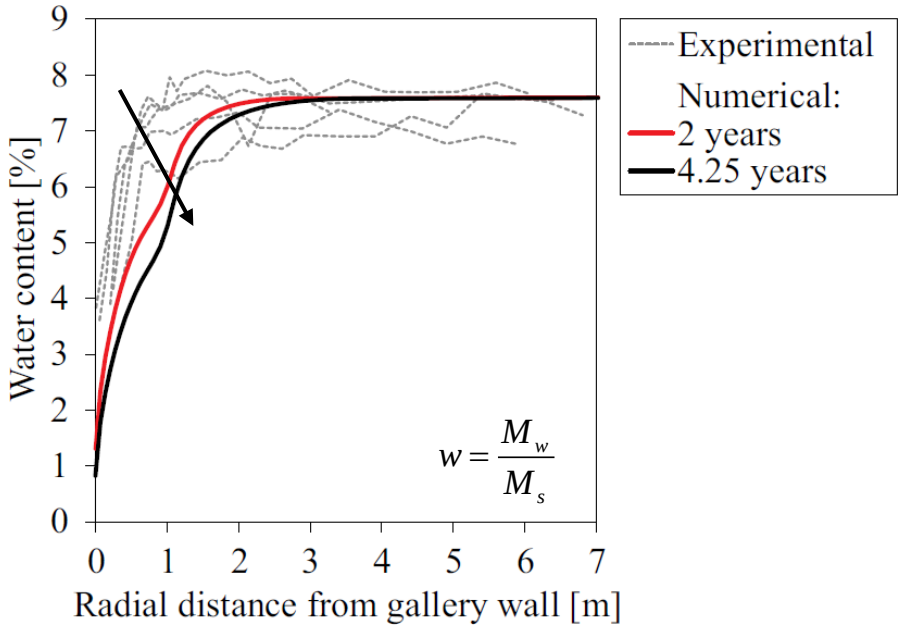


$\alpha_v = 10^{-3}$ m/s

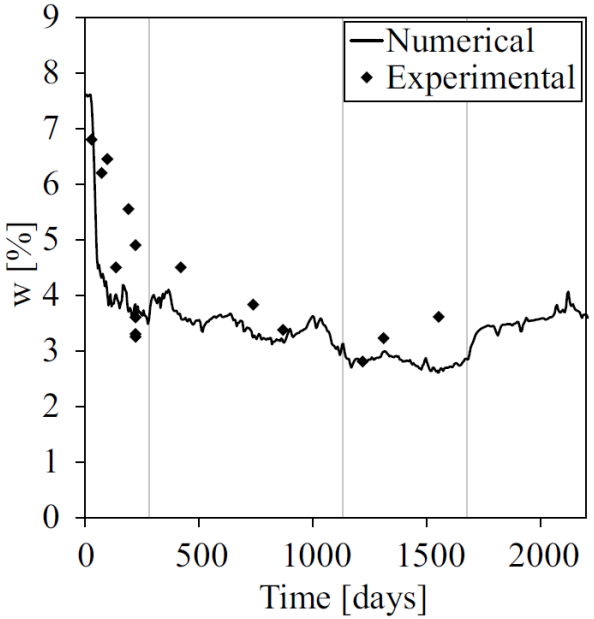
3. Permeability evolution

- Desaturation EDZ / w reproduction

Horizontal boreholes



At gallery wall



→ Desaturation: overestimation in long term

→ Vapour transfer ($\alpha_v = 10^{-3}$ m/s)

→ Good reproduction at gallery wall

Conclusions

Damaged zone → strain localisation zone similar to *in situ* measurements

→ modelling provide information about the rock structure and evolution within this zone, as observed *in situ*.

→ rock anisotropy and properties modification